Methods of the experimental investigation of mechanical action of radiations and particles fluxes on thin-walled constructions

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Abstract. The logic of tests and a set of gasdynamic devices for a research of strength of flight vehicle constructions taking place at mechanical action of radiations and particles are considered. Results of tests are briefly described. It is shown that now an efficient set of devices for modeling of mechanical action of radiations and particles on flight vehicles together with flight conditions is available.

Keywords: radiations and particules fluxes; mechanical action; flight vehicles: thin-walled constructions; gasdynamic devices.

1. Introduction

The direct experimental investigations of consequences taking place after the mechanical action (MA) of radiations and particles fluxes (RPF) located on elements of constructions of the flight vehicle (FV) are not represented possible. Direct irradiation is not realized as the absent of the powerful laboratory RPF sources that capable to generate necessary energy density distributed on surfaces having sizes about several meters [1, 2, 6]. In most cases rather reliable results are not achieved by means of models tests [16]. The difficulty arises from the fact that requirements of coincidence of criteria parameters for model and full-scale construction practically come down to identity last by the absolute sizes and properties of materials.

For example if the fuel charge for geometrically similar model of the FV Jet Engines of Solid Fuel (JESF) has the characteristic sizes which are not exceeding the critical size of a detonation then in this case detonation caused by action of mechanical RPF impulse is not impossible. But for the full-scale engine such detonation can take place. Similar difficulties arise also in attempt of modeling of nonstationary destruction in thin-walled composite construction of FV. The condition of similarity is equality of the relative thickness (h/R) of full-scale construction and its model when thickness of reinforcing thread remains invariable. This condition leads to reduction of number of layers of reinforcement at model. In turn this reduction of reinforcement layers distorts character and the sequence of destruction of these layers. Therefore the main methods of a research of RPF MA consequences are tests of full-scale FV constructions loaded by devices that simulate mechanical RPF action [6, 9, 11-14].

2. Logic of tests

Need of assessment of strength for the FV elements arises long before making

(a stage of designing and choice of the most optimal constructive solutions). However the composite materials which are widely applied in FV don’t exist separately from a construction. These materials are created along with a construction in the common technological process. Therefore experimental investigation of strength is possible only after making of composite constructions [15]. Nevertheless a part of researches is made on fragments. And only at a final stage the finishing tests of all construction are carried out. It is caused by the bigger cost of a composite construction in comparison with fragments. The set of the same elements can be made from one composite shell without loss of their strength. Besides creation of devices for generation of the low-pulse loadings having microsecond duration is difficult for big surfaces of natural constructions.

As is well-known nonstationary loadings are conditionally subdivided on pulse and dynamic according to features of the action and the reasons causing destruction of thin-walled constructions. Conditions of dynamic loading take place when duration is comparable with a period for free vibrations of thin-walled elements of FV constructions. The additional condition is that this duration more than by 10...15 times exceeds duration of waves propagation along shell thickness (this condition provides prevalence of a stage of deformation as a shell). At dynamic loading the destruction of thin-walled composite FV constructions happens owing to inadmissible deflections and formation of strafifications and cracks.

Pulse loading takes place when action duration doesn't exceed a quarter of a period of the free vibration and is comparable or less time of wave's propagation along construction thickness. In this case wave processes are the reason of stratifications (for composite materials) and spalls that leads to destruction of constructions. But even at pulse loading of thin-walled constructions process transforms into a stage of deformation as a shell. This transition is realized at attenuation of tension waves and growth of their spatial size up to the sizes commensurable with construction thickness. Besides use of porous sheetings significantly reduces a role of wave processes in destruction of a construction but practically doesn't protect from formation of cracks and inadmissible deflections. Therefore the finishing tests of strength of all construction to the dynamic loadings causing a stage of deformation as shell are useful and in that case when pulse action takes place only in condition.

We will note also that natural tests aren't required for a research of consequences of pulse loadings. Feature of such actions leading to wave destructions is their locality. As a rule it is possible to select a fragment from a construction and to put it in such conditions under which destructions of a fragment and the corresponding part of a construction are similar and occur at the same parameters of loadings.

Thus the research at strength of thin-walled constructions to mechanical RPF action is offered to be done in two stages [11, 13, 14] (see Fig. 1). At the first stage the detail research of wave processes and destructions caused by the action of impulse loads on fragments is necessary. If levels of wave damages were inadmissible (damages significantly influences at strength or
does not pass technical requirements) then construction is required to be upgraded. For example we can provide protection by means of the additional damping layers. The operability of new protection is required to be confirmed in final tests of the upgraded fragments.

At the second stage the completing tests of all construction having protective layers (if these layers are necessary according to results of the first stage) are required to be carried out in the conditions of its functioning and in case of action of the dynamic loads leading to the stage of shell deforming which develops after attenuation of wave processes. Carrying out the second test stage will be incorrect in case of simulation of flight conditions together with RPF MA reproduction that requires development of the appropriate devices.

Fig. 1. Scheme of carrying out tests

3. Gasdynamic devices

The gasdynamic method is the most convenient means of generation of non-stationary loadings [1, 2, 4-6]. In this method the action directed to a construction is carried out by a shock wave from charge of explosive material (EM) having the special form which provides the required spatial and temporary characteristics of loadings. Variations of energetic EM parameters allow to change amplitude and duration of loadings over a wide range and by an independent way. Besides a form of EM charger the change of loading parameters is carried out by:

- appropriate distribution of spatial EM density;
- method and temporary sequence of EM detonation;
- variation of characteristics of the separator located between the tested construction and a charge.

Duration and value of the pressure impulse generated by a gasdynamic method can vary in the range of 1…600 μs and 0,5…5 kPa times. Advantages of a gasdynamic method for RPF MA modeling are:

- possibility of test of large-size construction elements (linear sizes are about a meter and more);
- wide range of variation for a spatial and temporary profile of an impulse of pressure distributed on the loaded surface;
- technical simplicity of realization in field conditions.

3.1. Requirements to the modeling devices

Important preliminary stage of creation of devices set for modeling of RPF MA is the analysis of physics for RPF and substance interaction. On the basis of this analysis the requirement for parameters of non-stationary loadings distributed on surfaces of FV constructions have to be formulated. As an example we will consider requirements for devices modeling mechanical action of the radiations. The physics of radiation absorption realized in the condensed matter and streams of barrier changes depending on the wavelength (quantas energy). Therefore the physics of interaction of radiation and matter is considered separately for the following ranges of lengths of waves [6]:

- \(300\,\text{Å} < \lambda < 10^5\,\text{Å} (0,124\,\text{eV} < E_{ph} < 40 \,\text{eV})\) is radiation of optical range;
- \(10^5 < \lambda < 300\,\text{Å} (0,04 \,\text{keV} < E_{ph} < 1,24\,\text{keV})\) is ultrasoft X-ray radiation;
- \(1\,\text{Å} < \lambda < 10^5\,\text{Å} (1,24\,\text{keV} < E_{ph} < 12,4\,\text{keV})\) is soft X-ray radiation;
- \(0,1\,\text{Å} < \lambda < 1\,\text{Å} (12,4\,\text{keV} < E_{ph} < 124\,\text{keV})\) is rigid X-ray radiation.

Besides the wavelength the physics of interaction in many respects is defined by duration of the radiation impulse. The most powerful radiations sources having various wavelength ranges correspond to characteristic durations of generation. Therefore it is logical to consider physical processes of interaction of radiation and matter for the fixed region of wave’s lengths.
and only in a certain interval of change of impulses durations. Then for the fixed region of wave’s lengths and durations the surface density of energy can be defined from a condition of sufficiency of mechanical action parameters which are enough for damage of FV constructions. As a first approximation the irradiation parameters (wavelength, duration and surface density of energy) specified above and properties of barrier material and the environment are sufficient for definition of the regime of radiation and substance interaction.

Mechanical action of radiation of optical range was investigated in many papers (see review in [1]). Mechanical action is studied in detail as experimentally and theoretically in case of action of monochromatic radiation for the visible and infrared ranges and barriers which are airborne that is caused by existence of powerful pulse generators (for example lasers) in these ranges.

The range of wavelength studied in the atmosphere is limited by a condition of absence of air transparency for \( \lambda < 0.180 \mu m \) (actually narrower range 0.4 \( \mu m < \lambda < 0.1 \mu m \) was investigated in details). Vice versa the action of vacuum ultraviolet having length 0.1 \( \mu m < \lambda < 0.1 \mu m \) is practical interest when we consider case for absence of the air environment. A radiation of this wavelength range has the smaller divergence and bigger mechanical efficiency.

The regimes of action of optical radiation on the barrier surrounded with air are known much. But only the regime of a subsonic radiation wave and the regime of a light detonation can be of interest at a research of destruction for FV constructions by mechanical radiation action [1, 2, 6]. Pressure impulse \( g \) localized in the center of area of radiation \( g \) is estimated on a formula

\[
I_p = \eta W
\]

where \( W \) is surface density of energy, \( \eta \) is efficiency of mechanical action, \( (l_p) = \text{dyn/cm}^2 \). \( \eta = \text{dyn/J, } |W| = \text{J/cm}^2 \). It is possible to accept approximately for the regime of a subsonic radiation wave \( \eta = 10^6 \text{ dyn/cm}^2 \) and for the regime of a light detonation \( \eta = \text{10}^5 \text{ dyn/cm}^2 \) and for the regime of a light detonation \( \eta = \text{10}^5 \text{ dyn/cm}^2 \).

The dominating process of absorption taking place in vapor of barrier for ultra-violet radiation is photo effect. In this case the mass coefficient of absorption is rather big \( (\sigma_1 = 10^{10} \text{ cm}^2/\text{g}) \) and a small amount of the evaporated substance completely screens a barrier. The regime of heating and extension in vacuum for the gas having constant mass is realized [8]. The coefficient of mechanical efficiency is estimated on a formula \( \eta \geq 3.5 \text{ dyn HS/J} \) (for \( s \approx 0.4 \text{[6]} \))

\[
\eta = 32 W^{-1/2} E_p^{1/2}
\]

where \( s \) is an apparent exponent in the law \( \eta \approx (E_p)^s \).

The mechanical efficiency of action for ultra-soft X-ray radiation is estimated on a formula [6, 7] \( (\eta) = \text{dyn HS/J} \). [8]

\[
\eta = \frac{80}{\sqrt{Q_s}} \left[ \frac{2 \ln \gamma}{\gamma} \left( 1 - \frac{\ln \gamma}{\gamma} \right) \right]^{1/2}, \quad \gamma = \frac{\sigma_f W}{Q_s}
\]

where \( \gamma \) is the dimensionless parameter characterizing excess of the maximum absorbed energy over energy of sublimation (for ultra soft X-ray radiation \( \gamma \approx 1 \)).

Determination of parameters of mechanical action of X-ray radiation demands gasdynamic calculations taking into account heterogeneity of a barrier [2]. Existence of the air environment between an X-ray source and the irradiated object is the important circumstance influencing mechanical action. This influence is caused by essential change of power and temporary characteristics for the radiation impulse after passing of air layer. We will note that the case of the air environment isn’t of interest to soft X-ray (the insignificant amount of air absorbs practically all radiation). Presence of chemical elements having big atomic numbers \( \text{(Z} \geq 60) \) is essential also. These elements increase mass coefficient of radiation absorption that changes all physics of interaction between radiation and a barrier.

The carried-out analysis of calculations results and estimates on formulas (1)-(3) for the RPF MA parameters at various quanta energy and surface densities of energy taking into account properties of barrier materials and existence of the surrounding air environment allows to formulate requirements to modeling devices [1, 6]. These requirements are presented in table 1. As appears from this table loadings having parameters \( t = 0.01...300 \mu s \) and \( I_p = 0.02 ... 5 \text{ kPa HS} \) are required for RPF MA modeling. We will note that consideration of more complicated regimes of radiation action (cumulative; with a pre-impulse; frequentative, etc.) leads to a conclusion about need of creation of devices for generation of the loadings having the same impulses and durations but characterizing by complex spatially-temporally distributions [1, 6].

32 Devices for impulse loading [1, 6].

The Contact Sector Charge (CSC) generating loadings of microsecond duration is used most often for reproduction of mechanical X-ray action. The charge is made of the sheet EM broken for an exception of "knife effect" (the effect arises at interaction of the shock waves coming from various points of charge initiation) on small sectors having gaps between the neighboring parts “0.5 mm”. This charge is placed directly on the barrier or on the layer of porous material (the damper) connected to a barrier (see Fig. 2). Each sector of a charge is initiated in one point by a EM strip of minimum wideness “0.5 cm is enough for an invariable detonation” that practically excludes local explosive effect taking place in parts of gluing together of a charge and strip. Strips of identical length are gathered on the one hand in a bunch and are initiated by a high-speed detonator. The detonator is removed from the surface of loading and it doesn’t generate additional loading, negligible at design of a charge. Multipoint initiation provides simultaneity of applying of loading. Parameters of pulse loading generated by CSC depend on EM properties (density and the detonation speed of \( E_a \)) and barrier rigidity. Temporary change of pressure \( R(t) \) and an pressure impulse of are most just estimated in case of absolutely rigid wall [3]. Duration of loading action for the minimum thickness (0.03mm) of detonation for EM of type EEM-87 is about 1 \( \mu s \).
The multibarrelled Shock Tube of Explosive Action (STEA) is used for generation of the sequence of dynamic loadings (see Fig. 1). The simultaneity of blasting for EM is reached by multipoint initiation from one detonator by means of the strips of inert substrate. The substrate is removed on the stage of tests for durability of natural constructions to mechanical RPF action. This charge is elastic sheet EM placed on an equidistance around surface (see Fig. 3). The scheme of CSC for generation of ring waves consists of set of barrels that allows to generate separate loadings independently. Test stand including

<table>
<thead>
<tr>
<th>The radiation type</th>
<th>Radiation parameters</th>
<th>Influence conditions</th>
<th>Characteristics of loading</th>
<th>Number of the regime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visible and infrared radiations</td>
<td>$4 \times 10^{3} \ldots 10^{4}$</td>
<td>$0.5 \times 10^{-6}$</td>
<td>$10^{5}$</td>
<td>$0.50$</td>
</tr>
<tr>
<td>The ultraviolet radiation</td>
<td>$3 \times 10^{6} \ldots 10^{8}$</td>
<td>$0.1 \ldots 5$</td>
<td>$10^{6}$</td>
<td>$0.01 \ldots 1$</td>
</tr>
<tr>
<td>The ultra-soft X-ray radiation</td>
<td>$10 \ldots 300$</td>
<td>$0.1 \ldots 10$</td>
<td>$10^{8}$</td>
<td>$0.06 \ldots 0.5$</td>
</tr>
<tr>
<td>The soft X-ray radiation</td>
<td>$0.6 \ldots 10$</td>
<td>$0.1 \ldots 5$</td>
<td>$10^{7}$</td>
<td>$0.07 \ldots 1$</td>
</tr>
<tr>
<td>The hard X-ray radiation</td>
<td>$0.15 \ldots 10$</td>
<td>$0.1 \ldots 5$</td>
<td>$10^{4}$</td>
<td>$0.05 \ldots 1$</td>
</tr>
</tbody>
</table>

Table 1. Requirements to the devices modeling mechanical RPF action

(1 is a support; 2 is detonator; 3 is the initiating strips; 4,5 are ring sector parts of a charge; 6 is barrier; 7 is layer of porous rubber)

The contact charge detonating from light (CCDL) has been created for generation of the loading having smaller duration (it is less almost much in comparison with CSC) and receiving low pressure impulses. CCDL is used for modeling of mechanical action of soft X-ray for cases of low impulses. But CCDL is more expensive and less safe than CSC. Therefore CSC is used for generation of loadings having parameters $\tau_s \geq 0.2 \mu s$ and $p_\tau \geq 0.5 \text{kPa\ s}$.

### 3.3. Devices for dynamic loading

It is convenient if Equidistance and Superficial Charge (ESC) is used for generation of dynamic loadings at the second stage of tests for durability of natural constructions to mechanical RPF action. This charge is elastic sheet EM placed on an inert substrate. The substrate is removed on the set distance from an object and is equidistance allocated around surface (see Fig. 3). The simultaneity of blasting for EM is reached by multipoint initiation from one detonator by means of the strips of identical length made of sheet EM (it is similarly to the organization of initiation for CSC).

The Charge Distributed on Volume (CDV) has been created for generation of the dynamic loadings having duration lasting more than 100 $\mu s$. This charge is made of strips of low-energy EM. Loadings having duration $100 \ldots 500 \mu s$ and pressure pulses of $0.01 \ldots 2 \text{kPa\ s}$ can be modeled by means of CDV.

The explosive devices considered earlier are reserved for modeling of the single regime of RPF influence. But as is well-known loading in a resonance which takes place at repeated RPF influence is the most dangerous to thin-walled constructions. The multibarrelled Shock Tube of Explosive Action (STEA) is used for generation of the sequence of dynamic loadings (see Fig. 4). This shock tube consists of set of barrels that allows to generate separate loadings independently. Test stand including
STEA allows to load thin-walled constructions in the resonance regimes. Feedback from the sensor of displacement of the tested construction to the system of EM initiation realizes such regimes.

![Fig. 3. Equidistance and superficial EM charge](image1)

![Fig. 4. Shock tube of explosive action](image2)

Parameters of the described above and other devices [1, 6] are represented in table 2. It is visible that a set of devices allows to reproduce mechanical action of the radiation fluxes having characteristics from table 1.

<table>
<thead>
<tr>
<th>Type of explosive devices</th>
<th>Opportunities (characteristics of $\tau_p$, s $\rho$, kPa)</th>
<th>Application (the modelled regimes of influence)</th>
<th>Number of the regime from Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Sector Charge (CSC)</td>
<td>$10^{-6}...10^{-5}$, 0.8</td>
<td>monopulse influence of ultraviolet or X-ray</td>
<td>$2^<em>, 3^</em>, 5^* - 8^*$</td>
</tr>
<tr>
<td>Contact Charge Detonating from Light (CCDL)</td>
<td>$2 \times 10^{-7}...10^{-6}$, 0.05</td>
<td>monopulse influence of X-ray</td>
<td>$3^<em>, 4^</em>, 5, 7, 8^*$</td>
</tr>
<tr>
<td>Equidistance and Superficial Charge (ESC)</td>
<td>$10^{-5}...2 \times 10^{-4}$, 0.3</td>
<td>monopulse influence of visible or infrared radiations; in air</td>
<td>$1^*$</td>
</tr>
<tr>
<td>Electro-Digit Plasma Stand (EDPS)*</td>
<td>$5 \times 10^{-7}...5 \times 10^{-6}$, 0.01</td>
<td>monopulse influence of ultra-violet or ultrasoft X-ray</td>
<td>$3^<em>, 4^</em>, 5, 7, 8^*$</td>
</tr>
<tr>
<td>Charge Distributed on Volume (CDV)</td>
<td>$10^{-5}...5 \times 10^{-4}$, 0.1</td>
<td>monopulse influence of visible or infrared radiations; in air</td>
<td>1</td>
</tr>
<tr>
<td>Cumulative Charge Distributed on Volume (CCDV)</td>
<td>$10^{-5}...5 \times 10^{-4}$, 0.1</td>
<td>monopulse and cumulative influence of visible or infrared radiations; in air</td>
<td>1</td>
</tr>
<tr>
<td>Shock Tube of Explosive Action (STEA)</td>
<td>$5 \times 10^{-5}...2 \times 10^{-4}$, 0.5</td>
<td>pulse and frequency resonant influence of visible or infrared radiations; in air</td>
<td>$1^*$</td>
</tr>
<tr>
<td>Shock Tube of Explosive Action with Solid of Revolution (STEA SR)</td>
<td>$5 \times 10^{-5}...2 \times 10^{-4}$, 0.5</td>
<td>pulse and frequency influence of visible or infrared radiations having difficult spatial profile;</td>
<td>$1^*$</td>
</tr>
<tr>
<td>The system of the rotating EM charges</td>
<td>$10^{-1}...2 \times 10^{-4}$, 0.5</td>
<td>repeated impacts of radiations on high-temperature fluxes</td>
<td>-</td>
</tr>
</tbody>
</table>

* is this remark designated that the device reproduces appropriate regime only partially; * is this remark that this device isn’t gasdynamic.

4. Components for tests

4.1. Test stands and devices for modeling of flight conditions

In flight VF constructions are affected by trajectory loadings and are heated up from aerodynamic and thermal fluxes of the working JESF. In addition these constructions are irradiated with RPF fluxes [2]. Devices for modelling of flight conditions are required and used already during creation of new FV. Consideration of such devices is separate and very difficult subject. The used set of devices for modeling of flight conditions together with RPF MA are considered in work [1].

4.2. Methods of Measurements for parameters of reaction

As a rule the measurement of non-stationary deformations is carried out by an electrotensometric method according to the scheme of the balanced unary bridge. Sensors allowing to measure relative non-stationary deformation up to 4% and with a margin error is no more than 15% (for example strain gages of type KB-10-200) are used.

The high-frequency and vibration-proof sensors having high in transformation coefficient and the maximum value of the measured accelerations of $10^4$ g (for example the ADP-10-1 sensor having an error of measurements less than 20%) are used for measurement of overloads.

Temporary change of displacements is defined by means of optical methods. The residual deflection is defined by direct measurements of the internal sizes of a design before tests by means of micrometric or indicator devices. Use of these measuring devices together with special rigs allows to provide the absolute measurements accuracy of $\pm 0.1$ mm.
Sensors and errors of measurements for parameters of VF constructions reaction taking place at non-stationary side loading are considered in details [1].

5. Tests Results

The logic of tests and the device considered above were used at tests of various FV constructions for many years (since 1975). These tests have confirmed operability of this logic and a set of devices. We will note that of course a set of devices and methods of measurements of reaction parameters was improved throughout all this time.

5.1. First stage of tests

As it was already noted the first stage of tests is admissible to be carried out on fragments. Results of researches [11] for four types of protection from multilayered packages can be an example of the first stage of tests. Packages were tested as protection of constructions fragments from organ plastic and rubber. The high damping ability of these protective packages is shown.

5.2. Second stage of tests

The tests corresponding to the second stage were realized for a representative set of natural FV constructions. Strength tests of the working JESF are of the greatest interest [9]. The working JESF was tested on action of loading from ESC having the parameters \( l = 0.3 \text{kPa} \times \text{s} \) and \( \tau = 100 \mu \text{s} \). Such parameters don’t lead to fuel destruction as have shown calculations by means of mathematical model [10]. The mechanical action were made in the middle of operating engine time hasn’t exerted almost any influence on functioning of the engine. Inconsiderable changes in values of internal pressure and thrust force were observed only. It should be noted that non-stationary longitudinal deformation of expansion has pooled with static deformation (\( \epsilon_{\text{st}} \approx 1.5\% \)). As a result the common deformation has reached value \( \epsilon_{\text{tot}} \approx 1.6\% \) localize in the center of loading region. Such values of deformations are near to critical for organic plastics of cotton winding. The considerable overloads localized on the combustion chamber and in the place of fixing of a nozzle were observed also.

Mechanical action of CSC having an separator from porous rubber (\( l = 0.5 \text{kPa} \times \text{s} \) and \( \tau = 10 \mu \text{s} \)) leads to explosion of the engine at its further operation. In this case the fuel spall damages formed at reflection of a compression wave from the surface of burning are a cause of explosion of the engine. Further increase for a pressure impulse (\( l = 2 \text{kPa} \times \text{s} \) and \( \tau = 10 \mu \text{s} \)) leads to almost instant destruction of the damaged case by internal pressure (through time about 900 \( \mu \text{s} \) after CSC initiation). Longitudinal deformations at the time of loss of strength of the engine case have reached the value of \( \epsilon_{\text{tot}} \approx 2\% \).

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References